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RR Lyrae studies with *Kepler*: showcasing RR Lyr

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Abstract. Four years into the *Kepler* mission, an updated review on the results for RR Lyrae stars is in order. More than 50 RR Lyrae stars in the *Kepler* field are observed with *Kepler* and each one of them can provide us with new insight into this class of pulsating stars. Ground-based spectroscopy of the *Kepler* targets allows us to narrow down their physical parameters. Previously, we already reported a 50% occurrence rate of modulation in the RRab stars, a large variety of modulation behavior, period doubling in several Blazhko stars, the detection of higher-overtone radial modes, probable non-radial modes and new types of multiple-mode RR Lyrae pulsators, among both the RRab and the RRc stars. In addition, the quasi-continuous photometry obtained over several years with *Kepler* allows one to observe changes in Blazhko behavior and additional longer cycles. These observations have sparked new theoretical modelling efforts. In this short paper we showcase RR Lyr itself. The star has been observed with *Kepler* in short cadence, and some remarkable features of its pulsation behavior are unveiled in this long-studied prototype, through the *Kepler* photometry and additional spectroscopic data.

Keywords. stars: variables: RR Lyrae, stars: individual: RR Lyr, techniques: photometric, techniques: spectroscopic

1. Introduction

Kepler had been operational at full capacity for four years until the second of its four reaction wheels failed in May 2013, thereby compromising its capacity to point accurately. Towards the end of *Kepler*'s nominal mission time, over 40 RR Lyrae stars were known in the observed 115-square-degree field and all of them were included in the target list for the extended mission, which started in November 2012. More recently, several RR Lyrae stars have been found serendipitously, e.g., through the citizen science program "PlanetHunters" (www.planethunters.org), bringing the total of known *Kepler* RR Lyrae stars to about 50.

To complement the wide-band filter observations of the *Kepler* targets, Jeon *et al.* (these proceedings) have obtained extensive multicolor photometry for all the known RR Lyrae stars in the *Kepler* field. In addition, high-resolution spectroscopy has been obtained for 41 RR Lyrae stars in the *Kepler* field, leading to an accurate [Fe/H] determination for each one (Nemec *et al.* 2013). An overview of published studies (reviews excluded) on the

Table 1. RR Lyrae studies with *Kepler*, and spin-off studies/results published thus far.

Topic	Authors	N_{stars}	Remark[a]
First results (period doubling)	Kolenberg *et al.* (2010a)	2	A
Period doubling in *Kepler* data	Szabó *et al.* (2010)	3+4	A, M
Flavors of variability	Benkő *et al.* (2010)	29	A
Mathematical description of modulation	Benkő *et al.* (2011)		M, S
RR Lyr long-cadence data	Kolenberg *et al.* (2011)	1	A
Testing Stothers model on RR Lyr	Smolec *et al.* (2011)	1	A, M
Non-modulated RR Lyrae stars	Nemec *et al.* (2011)	19	A
Modeling of period doubling	Kolláth *et al.* (2011)		M
Radial resonance Blazhko model	Buchler & Kolláth (2011)		M, S
RRc multiperiodicity	Moskalik *et al.* (2012)	4	A
Nonlinear asteroseismology for RR Lyr	Molnár *et al.* (2012)	1	A, M
Multiperiodicity in V445 Lyr	Guggenberger *et al.* (2012)	1	A
(Quasi-)periodic modulation in BL Her stars	Smolec & Moskalik (2012)		M, S
Stitching together *Kepler* data of a Blazhko Star	Çelik *et al.* (2012)	1 (example)	A
Comparison of non-repetitive Blazhko cycles	Guggenberger (2012)	1	A
Metallicity [Fe/H], v_{rad}, etc. from spectra	Nemec *et al.* (2013)	41	A, G
RR Lyr in short cadence	Stellingwerf *et al.* (2013)	1	A
Additional RR Lyrae stars?	Kinemuchi (2013)	TBD	A, G
Chaotic pulsation models	Plachy *et al.* (2013)		M, S
Shock Blazhko model	Gillet (2013)	1 (example)	M
Ground-based multicolor data	Jeon *et al.* (these proc.)	41	G
Nonradial modes or not?	Benkő (these proc.)	41	A
Interchange of alternating amplitudes	Plachy *et al.* (these proc.)	3	A
Multi-mode resonances in RR Lyrae stars	Molnár *et al.* (these proc.)	4	A, M

[a] A: Analysis, M: Modelling, G: Ground-based data, S: Spin-off.

Kepler data and their spin-offs is given in Table 1. In this paper we focus on the brightest RR Lyrae star in the *Kepler* field, RR Lyr.

2. Showcasing RR Lyr

The analysis of the long-cadence *Kepler* data of RR Lyr (quarters Q1 – Q2, May – September 2009) was published by Kolenberg *et al.* (2011). As of Q5 (March 2010) the star was observed in short cadence. Molnár *et al.* (2012) found evidence for the first radial overtone in the Q5 and Q6 short-cadence data. A frequency analysis performed on the Q5 – Q15 short-cadence data (March 2010 – January 2013) leads to the following conclusions (see also Stellingwerf *et al.* 2013):

- There is clear evidence for a longer cycle in RR Lyr. A cycle of duration of about 4 years was reported by Detre & Szeidl (1973). The Blazhko amplitude variation of about 40% at the beginning of the *Kepler* measurements decreases significantly (to as low as 0-10% in light amplitude) and then increases again (see Fig. 1).
- There is a variation of the 0.5667-day pulsation period (from 0.5655 to 0.5685 day) within each Blazhko cycle, with the shorter period corresponding to the larger amplitude phases in the Blazhko cycle. This variation of half a percent is huge considering that the mean period has barely changed since the observations by Shapley (1916).
- There is a variation of the Blazhko period itself (from 39.2 days at maximum Blazhko amplitude to 38.4 days at the amplitude minimum) over the 4-year modulation cycle, i.e., about 2%.
- There is a small but detectable variation (a few mmag) of the mean brightness over the Blazhko cycle.

Spectroscopic data allow an in-depth analysis of the pulsations of RR Lyrae stars (see also Guggenberger, these proceedings). A spectroscopic data set of RR Lyr, obtained with the high-resolution ($R = 60\,000$) spectrograph attached to the 2.7-m telescope at McDonald Observatory was described by Kolenberg *et al.* (2010b). Integration times were

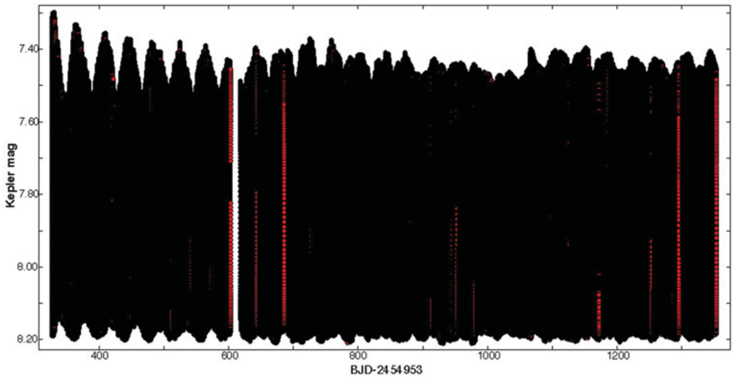

Figure 1. *Kepler* short-cadence data of RR Lyr (Q5–Q15). Individual cycles are not visible, but the envelope of the Blazhko modulation is. There is clear evidence for a variation in the strength of the Blazhko effect.

typically 20 minutes. A detailed abundance analysis was performed on the spectrum in the most quiescent phase in RR Lyr's pulsation cycle. This is the phase when the star reaches its maximum radius, around pulsation phase ∼0.3 for RR Lyr.

We fitted a static Kurucz atmosphere model to the spectrum in the most quiescent phase. Using an instrumental profile of 5 $\mathrm{km\,s^{-1}}$ (corresponding to the instrumental resolution), the best fit is obtained for a macroturbulent velocity $v_{\mathrm{mac}} = 5 \pm 2$ $\mathrm{km\,s^{-1}}$ and a projected rotational velocity $v \sin i = 5 \pm 2$ $\mathrm{km\,s^{-1}}$.

Short-cadence spectroscopy was obtained simultaneously with the short cadence *Kepler* data over three nights in 2010 (Kolenberg *et al.*, in preparation). With a 1-minute spectrum taken every few minutes the photospheric layers can be followed in detail over time. In Fig. 2 we show the radial-velocity variations for two spectral lines, the Hγ line at 4340.462 Å and a Cr line at 4351.811 Å, over a few hours of spectra coinciding with the descending branch (declining light) of the star (pulsation phase [0.0 − 0.35]). We can detect shifts of 1 $\mathrm{km\,s^{-1}}$ for spectra taken only four minutes apart, even in this "quieter" phase interval of the pulsation cycle. As a consequence, spectra taken over 20 minutes, an integration time necessary to obtain a sufficient signal-to-noise ratio for a detailed line profile analysis on a 3-m class telescope, show smearing of the order of 5 $\mathrm{km\,s^{-1}}$. That

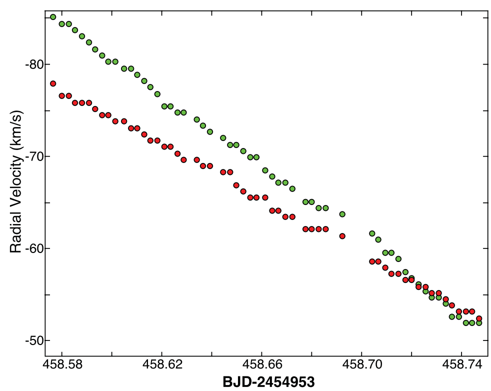

Figure 2. Radial velocities derived from two lines for the short-cadence spectra. The steeper radial-velocity curve corresponds to the Hγ line, the other one to the Cr line.

implies that the macroturbulent velocity parameter $v_{\rm mac} = 5$ km s^{-1} adopted in our fit to the observed spectrum is probably a representative lower limit.

Assuming $v \sin i = 5$ km s^{-1} implies, for a star with a radius of about $5\,R_\odot$, that $P_{\rm rot} \sim 50$ d $\times \sin i$. As a consequence, rotation period and Blazhko period could correspond, which is an essential component in some models for the Blazhko effect (Shibahashi & Takata 1995; Dziembowski & Mizerski 2004), though currently not the most favored explanation. The observation of changing or multiple modulation periods does pose a problem for the models linking the modulation directly to the rotation, but one could think of a scenario in which features at different latitudes on the star rotate at different speeds, translated into the light variation. However, often the observed modulation periods for a given star are sometimes too far apart (e.g., 40 days and 120 days) to make this a plausible scenario.

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